Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 5 February 2008 (MN LATEX style file v2.2)

The late time evolution of Gamma-Ray Bursts: ending hyperaccretion and producing flares

Daniel Proga[1] and Bing Zhang[1]
[1] Department of Physics, University of Nevada, Las Vegas, NV 89154, USA, e-mail: dproga@physics.unlv.edu; bzhang@physics.unlv.edu

Accepted . Received ; in original form

ABSTRACT
We consider the properties of a hyperaccretion model for gamma-ray bursts (GRBs) at late times when the mass supply rate is expected to decrease with time. We point out that the region in the vicinity of the accretor and the accretor itself can play an important role in determining the rate of accretion, and its time behavior, and ultimately the energy output. Motivated by numerical simulations and theoretical results, we conjecture that the energy release can be repeatedly stopped and then restarted by the magnetic flux accumulated around the accretor. We propose that the episode or episodes when the accretion resumes correspond to X-ray flares discovered recently in a number of GRBs.

Key words: accretion, accretion discs – gamma rays: bursts – methods: numerical – MHD

1 INTRODUCTION

Gamma-Ray Bursts (GRB) are generally believed to be powered by hyperaccretion onto a compact, stellar mass object. The total amount of the available fuel is considered to be the key factor determining the burst duration. Within merger scenarios for short-duration GRBs, a neutron star (NS) is accreted onto another NS or onto a stellar mass black hole (BH; e.g, Paczyński 1986, 1991; Eichler et al. 1989; Narayan et al. 1992; Fryer et al. 1999). Within the collapsar model for long-duration GRBs, up to 20 $\mathrm{M}_{\odot}$ of a stellar envelope collapses onto the star's core which is a NS or a BH (e.g., Woosley 1993; Paczyński 1998; MacFadyen & Woosley 1999; Popham, Woosley, & Fryer 1999; Proga et al. 2003). For short- and long-duration events, the accretion rate, $\dot{M}_a$ must be of order of $1\ \mathrm{M}_{\odot}\ \mathrm{s}^{-1}$, yielding a duration of less than a few seconds for the former and a duration as long as tens to hundreds of seconds for the latter. These duration estimates are made under the assumption that all the available fuel is accreted during the GRB activity at a time-averaged constant rate.

Recent GRB observations obtained with *Swift* motivate us to review the above assumption and some other aspects of GRB models. In particular, early X-ray afterglow lightcurves of nearly half of the long-duration GRBs show X-ray flares (Burrows et al. 2005; Romano et al. 2006; Falcone et al. 2006). X-ray flares are also found to follow the short-duration GRB 050724 (Barthelmy et al. 2005) whose host galaxy is early-type, which is consistent with the merger origin. The flares generally rise and fall rapidly, with typical rising and falling time scales much shorter than the epoch when the flare occurs. This time behavior strongly supports the "internal" origin of the flares (Burrows et al. 2005; Zhang et al. 2006; Fan & Wei 2005), in contrast to the "external" origin of the power-law decay afterglows. The internal model not only offers a natural interpretation of the rapid rise and decay behavior of the flares, but also demands a very small energy budget (Zhang et al. 2006). Within this picture, the data require a *restart* of the GRB central engine (i.e., a restart of accretion).

Fragmentations in the collapsing star (King et al. 2005) or in the outer parts of the accretion disc (Perna et al. 2006) have been suggested to be responsible for the observed episodic flaring behavior. These two flare models appeal to one of the basic ingredients of an accretion powered engine – the mass accretion rate – and conjecture that the episodic energy output is driven by changes in the mass supply and subsequently accretion rate. In this picture, the inner part of the accreting system *passively* responds to changes in the accretion flow at larger radii.

Here, we point out that the region in the vicinity of the accretor and the accretor itself can play an important role of determining the rate and time behavior of the accretion and the energy output. In particular, we conjecture that the energy release can be repeatedly stopped and then restarted, provided the mass supply rate decreases with time even if the decrease is smooth. For both merger and collapsar GRB models, a decrease of the mass supply rate is expected, especially in the late phase of activity, because the mass density decreases with increasing radius. In our model, we appeal to the fact that, as mass is being accreted onto a BH, the magnetic flux is accumulating in the vicinity of the BH. Eventually, this magnetic flux must become dynamically important and affect the inner accretion flow, unless the magnetic field is very rapidly diffused. In the remaining part of the paper we list and discuss theoretical arguments and results from a variety of numerical magnetohydrodynamic (MHD) simulations of accretion flows that support our model. We also provide analytic estimates to show that our model can quantitatively account for the observed features of the flares.

2 MAGNETIC MODEL FOR GRBS AND THEIR FLARES

2.1 Insights from numerical models

Generally, our model for the flares is based on the results from the numerical simulation of an MHD collapsar model for GRBs carried out by Proga et al. (2003) and the results from a number of simulations of radiatively inefficient accretion flows (RIAFs) onto a BH (Proga & Begelman 2003, PB03 hereafter; Igumenshchev, Narayan, &Abramowicz 2003, INA03 hereafter). Proga et al. (2003) performed time-dependent axisymmetric MHD simulations of the collapsar model. These MHD simulations included a realistic equation of state, neutrino cooling, photodisintegration of helium, and resistive heating. The progenitor was assumed to be spherically symmetric but with spherical symmetry broken by the introduction of a small, latitude-dependent angular momentum and a weak split-monopole magnetic field. The main conclusion from the simulations is that, within the collapsar model, MHD effects alone are able to launch, accelerate and sustain a strong polar outflow. The MHD outflow provides favorable initial conditions for the subsequent production of a baryon-poor fireball (e.g., Fuller, Pruet & Abazajian 2000; Beloborodov 2003; Vlahakis & Königl 2003; Mészáros 2002), or a magnetically dominated "cold fireball" (Lyutikov & Blandford 2002), though the specific toroidal magnetic field geometry Proga et al. derived differs from some of these models (e.g., Vlahakis & Königl 2003; Lyutikov & Blandford 2002). The latest Swift UV-Optical Telescope (UVOT) observations indicate that the early reverse shock emission is generally suppressed (Roming et al. 2005), which is consistent with the suggestion that at least some GRBs are Poynting-flux-dominated outflows (Zhang & Kobayashi 2005).

To study the extended GRB activity, one would like to follow the collapse of the entire star. However, such studies are beyond current computer and model limits. Therefore, we explore instead the implications of the published simulations and consider the physics of the collapsing star to infer the properties and physical conditions in the vicinity of a BH during the late phase of evolution, i.e., when a significant fraction of the total available mass is accreted.

The long time evolution of axisymmetric MHD accretion flows was studied by PB03 who explored simulations very similar to those performed by Proga et al. (2003) but with much simpler micro physics (i.e., an adiabatic equation of state, no neutrino cooling or photodisintegration of helium). Proga et al. (2003) found that despite the more sophisticated micro physics of the MHD collapsar simulations the flow cooling is dominated by advection not neutrino cooling. As a result, the early phase of the time evolution, and the dynamics of the innermost flow, are very similar in both the RIAF simulations and the collapsar simulations. In particular, after an initial transient behavior, the flow settles into a complex convolution of several distinct, time-dependent flow components including an accretion torus, its corona and outflow, and an inflow and outflow in the polar funnel (see the left panel in Fig. 1 for a schematic picture of such a flow). The accretion through the torus is facilitated by the magnetorotational instability (MRI, e.g., Balbus & Halwey 1991) which also dominates the overall dynamics of the inner flow.

In the remaining part of the paper, we will assume that the late evolution of the MHD collapsar simulations is similar to the late evolution of the RIAFs simulations. This assumption is justifiable because the flows in the collapsar and RIAFs simulations are similar during the early phase of the evolution (i.e., their dymanics and cooling are dominated by MRI and advection, respectively)

The late evolution of RIAFs shows that the torus accretion can be interrupted for a short time by a strong poloidal magnetic field in the vicinity of a BH. This result is the main motivation for this paper, as it shows that the extended GRB activity may be a result of an accretion flow modulated by the "magnetic-barrier" and gravity. Because this barrier halts the accretion flow intermittently (see Figs. 6 & 8 in PB03), the accretion rate is episodic (see Fig.3 of PB03). This potentially gives a natural mechanism for flaring variability in the magnetic-origin models of GRBs as we first mentioned in Fan, Zhang & Proga (2005; see the middle panel of Fig. 1 here, for a cartoon picture of the accretion halted by the magnetic-barrier.)

The importance of accumulating of the magnetic flux has been explored and observed by others in various astrophysical contexts (e.g., Bisnovatyi-Kogan & Ruzmaikin 1974, 1976; Narayan, Igumenshchev & Abramowicz 2003; INA03). In particular, INA03 carried out a three-dimensional (3D) MHD simulation (their model B) to late model times. They found that the magnetic flux accumulates, initially near the BH and then farther out, and the field becomes dynamically dominant. At late times, mass is able to accrete only via narrow streams, in a highly nonaxisymmetric manner (see also Narayan et al. 2003).

The main difference between PB03's and INA03's results is the extent and duration of the magnetic dominance. In PB03, the magnetic dominance is a *transient* whereas in INA03 is a *persistent* state. The reason for this difference is the treatment of the magnetic field: for the initial conditions, PB03 used the split-monopole magnetic field and any changes in the magnetic flux near the BH during the evolution are due to the chaotic, small-scale fields generated in the disc. The detailed analysis show that the disc properties in PB03's simulations are determined by MRI. In particular, MRI is responsible for the complex field structure and for the disc toroidal field being one or even two orders of magnitude higher than the poloidal field (see figs. 9 and 10 in PB03 and fig. 3 in Proga et al. 2003). On the other hand, in their model B, INA03 set up a poloidal field configuration in the injected gas in such a way that the portion of the material that accretes always carries in the same sign of the vertical component of the magnetic field. The simulations carried out by PB03 and INA03 differ also in the assumed geometry (axisymmetric versus fully 3D). INA03 and PB03 do not explore all cases including the case where the external or initial field has zero net flux or the field with the poloidal component changing sign on length scales much smaller than the size of the mass reservoir [1]. Additionally, these simulations also do not give definitive answers to the problems for which they were designed. Nevertheless, they give interesting insights into the general problem of MHD accretion flows. In particular, they suggest that magnetic fields can provide an important parameter determining the time scale for the accretion; i.e., it can be significantly longer than the local dynamical time scale. This can have important implications for the observed X-flares in GRBs, as we argue here, and for X-ray spectral states for BH binaries as discussed by Spruit & Uzdensky (2005, SU05 hereafter). In fact, the work by SU05 describes very well the general physics and theory of magnetic flux accumulated by an accretion flow. Therefore we now turn our attention to some theoretical aspects of the problem as presented by SU05.

[1] In the case where the initial or external flux has zero-net flux, a large scale coherent field might in some circumstances be generated by MRI (e.g., Livio, Pringle, & King 2003). If so the central magnetic flux could vary with time but still be dynamical signifacant for some periods of time.

2.2 Theory of the magnetic barrier and accretion flow

SU05 considered a new mechanism of efficient inward transport of the large-scale magnetic field through a turbulent accretion disc. The key element of the mechanism is concentration of the external field into patches of field comparable in strength to the MRI turbulence in the disc. They focused on how to increase the magnetic flux at the center in the context of BH binaries. In particular, they argue that the capture of external magnetic flux by accretion disc and its subsequent compression in the inner regions of the disc may explain both changes in the radiation spectrum and jet activity in those objects. However, their model and physical arguments are generic and applicable to our problem.

One can expect that as the strength of the magnetic field increases at the center, the field may eventually suppress MRI turbulence and reduce the mass accretion rate and the power in the outflow. This should be the case especially for GRBs because the mass inflow rate at the late time is most likely much lower than at the early time. The disc may become a Magnetically-Dominated Accretion Flow (MDAF) as proposed by Meier (2005) or the fields in the polar funnel can expand toward the equator and reconnect as in PB03's simulations. In the latter, the torus is pushed outward by the magnetic field. At this time, the gas starts to pile up outside the barrier; eventually it can become unstable to interchange instabilities at the barrier outer edge as suggested by SU05 or the gas in the torus can squash the magnetic field (compare Fig. 5 and 6 in PB05 or the middle and right panel in Fig.1 here).

When interchange instabilities operate, magnetic flux from the bundle mixes outward into the disc while the disc material enters the barrier. In the accretion disk context, interchange instabilities have been studied by a few authors (e.g., Spruit et al. 1995; Lubow & Spruit 1995; Stehle 1996; Stehle & Spruit 2001; Li & Narayan 2004). These studies showed that the onset of small-scale modes typical of interchanges (as in Rayleigh-Taylor instabilities) takes place only at rather large field strengths, due to a stabilizing effect of the Keplerian shear. The interchange instability operates at moderate field strengths, but only at low shear rates (less than Keplerian). However for most of the time, we expect high shear rates in a torus because a low shear torus quickly becomes Keplerian due to MRI (e.g., PB03 and Proga et al. 2003). We note that SU05 interpreted INA03 accretion through the barrier, in the form of blobs and streams as a product of interchange instabilities.

SU05 also suggested that the field strength at which these instabilities become effective is most usefully expressed in terms of the degree of support against gravity provided by the magnetic stress $B_R B_Z$. According to SU05, the instabilities become effective when the radial magnetic force, $F_m \sim 2B_R B_Z/4\pi$, is of the order of a few percent of the gravitational force, $F_g = GM\Sigma/R^2$, where M is the central mass, R is the radius, and Σ is the surface density. For $B_R \approx B_Z$, there is a range in field strengths between the value at which MRI turbulence is suppressed and the value where dynamical instability of the barrier itself sets in, where no known instability operates (Stehle & Spruit 2001). In this range, the disk material cannot mix or penetrate the magnetic field accumulated at the center (e.g., the middle panel of Fig. 1). Instead, mass builds up outside a region with such field strengths until the magnetic field at the center is compressed enough for instability to set in.

Thus, both numerical work and theoretical models of magnetized accretion flows show that the inner most part of the flow and accretor can respond *actively* to changes of the accretion flow at larger radii. In particular, the inner most accretion flow can be halted for a very long time as shown by INA03 or it can be repeatedly halted and reactivated as shown in PB03.

2.3 Analytic estimates

We finish this section with order-of-magnitude estimates of a few key features of our X-ray flare model. We start by estimating the strength and flux of magnetic field required to support the gas. The gas of the surface density, Σ can be supported against gravity by the magnetic tension if $F_g \sim F_m$. The surface density can be estimated from $\Sigma = \dot{M}/2\pi R\epsilon v_{ff}$ g cm^{-2}, where ϵv_{ff} is the flow radial velocity assumed to be a fraction ϵ of the free fall velocity, v_{ff}. Assuming $B_r \approx B_z = B$, the force balance yields the field strength $B \sim 2\times10^{16}\ \epsilon_{-3}^{-1/2} r^{-5/4} \dot{M}_1^{1/2} M_3^{-1}$ G, where $\epsilon_{-3} \equiv 10^3\epsilon$, $r \equiv R/R_S = R/(2GM_{BH}/c^2)$, $\dot{M}_1 = \dot{M}/1\ \mathrm{M_\odot\ s^{-1}}$, and $M_3 = M/3\mathrm{M_\odot}$. We estimate the magnetic flux as $\Phi \sim \pi r^2 R_S^2 B(r) = 5\times10^{28}\ \epsilon_{-3}^{-1/2} r^{3/4} \dot{M}_1^{1/2} M_3\ \mathrm{cm^2\ G}$ from which we obtain an estimate to the magnetospheric radius $r_m \approx 60\ \epsilon_{-3}^{2/3} \dot{M}_1^{-2/3} M_3^{-4/3} \Phi_{30}^{4/3}$, where $\Phi_{30} \equiv \Phi/(10^{30}\ \mathrm{cm^2 G})$. Substituting the expression for B into the expression for the surface density, one finds that a given magnetic flux can support the gas with the surface density of $\Sigma_B = 5\times10^{19}\ \Phi_{30}^2 M_3^{-3} r^{-2}$ g cm^{-2}.

To stop accretion with the hyper rate of $1\mathrm{M_\odot\ s^{-1}}$ onto a $3\mathrm{M_\odot}$ black hole at r=3 (i.e., for r_m to be 3), the magnetic flux of order $\Phi_{30} \sim 0.11$ is required. We now assume that such a magnetic flux is accumulated during hyperaccretion and that it does not change with time. Under these assumptions, $r_m = 300$ for the mass supply rate of $10^{-3}\ \mathrm{M_\odot\ yr^{-1}}$ representative of the late time evolution . This relatively large radius demonstrates one of our key points that the innermost part an accreting system can actively respond, via magnetic fields, to changes in the inflow at large radii.

To estimate the conditions needed to restart accretion, the accretion energetics and related time scales, we ask what is the mass of a disc with Σ high enough to reduce r_m from 300 to 3 or so. To answer this question, we adopt Popham et al.' (1999) model of neutrino-dominated discs. Popham et al. assumed that neutrino cooling produces a thin disc (Shakura & Sunyaev 1973) for accretion rates require to power GRBs. Using the disc solution for the density and height (eqs. 5.4 and 5.5 in Popham et al. 1999), we can express the disc surface density as $\Sigma_\alpha = 1.8\times10^{19}\ \alpha^{-1.2} M_3^{-0.8} \dot{M}_1 r^{-1.25}$ g, where α is the dimensionless parameter scaling the stress tensor and the gas pressure (Shakura & Sunyaev 1973). Equating Σ_B with Σ_α, one can estimate the mass accretion rate of an α disc and compute M_D by integrating Σ_α over radius. For $\Phi_{30} = 0.11$ and $\alpha = 10^{-2}$ the accretion rate through the α disc is 0.03 $\mathrm{M_\odot\ s^{-1}}$ and M_D for r between 3 and 300 is 0.32 $\mathrm{M_\odot}$. This mass accretion rate is more than one order of magnitude lower than the rate of $\sim 1\ \mathrm{M_\odot\ s^{-1}}$ typical for the early time evolution. Thus, our estimates are consistent with the fact that the X-ray flare luminosity is at least one or two orders of magnitude lower the prompt gamma-ray emission (see section 3). If this disc mass is a result of slow mass accumulation during the late evolutionary stage, then it will take about 400 s to rebuild the disc for the mass supply rate of $10^{-3}\ \mathrm{M_\odot\ s^{-1}}$ and 12 s to accrete all this mass at the disc accretion rate of $0.03\ \mathrm{M_\odot\ s^{-1}}$. The latter is a lower estimate for the flare duration because, for simplicity, we assumed a relatively high, *constant* disc accretion rate. It is very likely that the rate changes with time as the shape of the light curve during the flares indicates. In our model, the mass supply rate controls the epochs when the flares happen: the disc is rebuilt on the time scale which increases with time because the mass supply

slowdowns. Additionally, the flare duration is coupled to the epoch through the mass of the rebuilt disc. Thus our model is capable of accounting for the observed duration - time scale correlation.

3 DISCUSSION AND CONCLUSIONS

The detailed analysis of the X-ray flares revealed that they generally have lower luminosities (by at least one or two orders of magnitude) than the prompt gamma-ray emission. Additionally, the total energy of the flare is also typically smaller than that of the prompt emission, although in some cases both could be comparable (e.g. for GRB 050502B, Falcone et al. 2006). Moreover multiple flares are observed in some GRBs and the durations of these flares seem to be positively correlated with the epochs when the flares happen, i.e. the later the epoch, the longer the duration (O'Brien et al. 2005; Falcone et al. 2006; Barthelmy et al. 2005). The flare analysis also showed that the later the epoch the lower the flare luminosity. The above qualitative properties of the flares provide important constraints on models of them.

Perna et al.'s (2006) disc fragmentation model promises to account for the duration - time scale correlation and the duration - peak luminosity anticorrelation. However, the physical process or processes causing fragmentation are uncertain. It is also uncertain that the conditions for the disc fragmentation are met in GRB progenitors. This seems to be the case especially for the collapsar model as a relatively high rotation of the progenitor is required. We also note that magnetic fields can suppress or even prevent disc fragmentation (e.g., Banerjee & Pudritz 2006).

Here, we propose that the X-ray flares in GRBs are consequences of the fact that during the late time evolution of a hyperaccretion system the mass supply rate should decrease with time while the magnetic flux accumulating around a BH should increase. In particular, we point out that the flux accumulated during the main GRB event can change the dynamics of the inner accretion flow. We argue that the accumulated flux is capable of halting intermittently the accretion flow. In our model, the episode or episodes when the accretion resumes correspond to X-ray flares. A comparison of our analytic estimates from Section 2.3 with the observed X-ray flare characteristics, shows that our model is not only physically based but also can both qualitatively and quantitatively account for some aspects of the flares – such as the peak times. In general, our model fits under the general label of the magnetic jet model for GRBs as we appeal to the magnetic effects to play the key role not only during the main event but also during the late evolution. The importance of the magnetic effects for the X-ray flares can be argued based on energy budget of the accretion model (Fan et al. 2005).

The X-ray flares discovered in GRBs are relatively new and unexpected phenomena. They give a strong incentive to apply the existing models of hyperaccretion systems to circumstances where the mass supply is reduced. Studies of this kind should reveal whether one needs to introduce additional physics in order to explain the flares. If so one should explore the effects of this on the early evolution of GRBs and check whether they are consistent with GRBs observations. Our X-ray flare model has the advantage that it is essentially the same as the MHD collapsar model for GRBs, with only one justifiable change in a key physical property of the collapsar model: a decrease of the mass supply rate with time.

ACKNOWLEDGMENTS

We thank D. Meier, D. Uzdensky, and a referee for useful comments. This work is supported by NASA under grants NNG05GB68G (DP) and NNG05GB67G (BZ).

REFERENCES

Balbus, S. A., & Hawley, J. F. 1991, ApJ, 376, 214
Banerjee R., & Pudritz R.E. 2006, ApJ, 641, 959
Barthelmy, S. D., et al. 2006, Nature, 438, 994
Beloborodov, A.M. 2003, ApJ, 588, 931
Bisnovatyi-Kogan, G.S., & Ruzmaikin, A.A. 1974, Ap&SS, 28, 45
Bisnovatyi-Kogan, G.S., & Ruzmaikin, A.A. 1976, Ap&SS, 42, 401
Burrows, D. N. et al. 2005, Science, 309, 1833
Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Nature, 340, 126
Falcone, A. et al. 2006, ApJ, 641, 1010
Fan, Y. Z., & Wei, D. M. 2005, MNRAS, 364, L42
Fan, Y. Z., Zhang, B. & Proga, D. 2005, ApJ, 636, L129
Fryer, C. L., Woosley, S. E., & Hartmann, D. H. 1999, ApJ, 526, 152
Igumenshchev, I.V., Narayan, R., & Abramowicz, M.A. 2003, ApJ, 592, 1042, INA03
King, A. et al. 2005, ApJ, 630, L113
Li, L.-X. & Narayan, R. 2004, ApJ, 601, 414
Livio, M., Pringle, J.E., & King, A.R. 2003, 593, 184
Lubow, S. H., & Spruit, H. C. 1995, ApJ, 445, 337
Lyutikov, M. & Blandford, R. 2002, APS, APR, 6008
MacFadyen, A., & Woosley, S.E. 1999, ApJ, 524, 262
Meier, D. in "X-ray Binaries to Quasars: Black Hole Accretion on all Mass Scales", (astro-ph/0504511)
Mészáros, P. 2002, ARA&A, 40, 137
Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A. 2003, PA SJ, 55, L69
Narayan, R., Paczyński, B., & Piran, T. 1992, ApJ, 395, L83
Narayan, R., Piran, T., & Kumar, P. 2001, ApJ, 557, 949
O'Brien, P. T. et al. 2005, ApJ, submitted (astro-ph/0601125)
Paczyński, S. 1986, ApJ, 308, L43
Paczyński, S. 1991, Acta Astron., 41, 257
Paczyński, B. 1998, ApJ, 494, L45
Perna, R., Armitage, P. J. & Zhang, B. 2006, ApJ, 636, L29
Popham, R., Woosley, S. E., & Fryer, C. 1999, ApJ, 518, 356
Proga, D. & Begelman, M. C. 2003, ApJ, 592, 767, PB03
Proga, D., MacFadyen, A. I., Armitage, P. J. & Begelman, M. C. 2003, ApJ, 599, L5
Roming, P. W. A. et al. 2005, ApJ, submitted (astro-ph/0509273)
Romano, P. et al. 2007, A&A, 450, 59
Spruit, H. C., Stehle, R., & Papaloizou, J. C. B. 1995, MNRAS, 275, 1223
Spruit, H. C., & Uzdensky, D. A. 2005, ApJ, 629, 960, SU05
Stehle, R. 1996, Ph.D. thesis, Univ. Amsterdam
Stehle, R., & Spruit, H. C. 2001, MNRAS, 323, 587
Shakura N.I., & Sunyaev R.A. 1973 A&A, 24, 337
Vlahakis, N., & Königl, A. 2003, ApJ, 596, 1104
Woosley, S.E. 1993, ApJ, 405, 273
Zhang, B., Fan, Y. Z., Dyks, J., Kobayashi, S., Mészáros, P., Burrows, D. N., Nousek, J., & Gehrels, N. 2006, ApJ, 642, 354
Zhang, B. & Kobayashi, S. 2005, ApJ, 628, 315

This paper has been typeset from a TEX/ LATEX file prepared by the author.

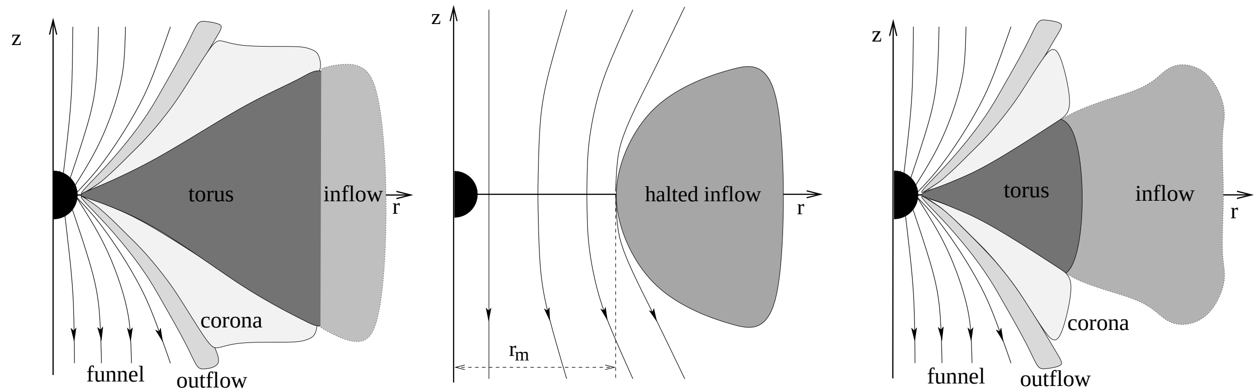

Figure 1. From left to right: General structural features of the inner MHD flow at three different accretion stages: 1) the inner flow during the hyperaccretion when a relativistic jet forms and a strong poloidal magnetic field is being accumulated at the center. The hyperaccretion can not be sustained because the mass supply rate from the outer inflow drops with time (hence different shades used for the torus and inflow). 2) The flow when the hyperaccretion ended and the inflow rate is relatively low. During this stage the magnetic field that accumulated earlier, can support the gas against gravity. Consequently the inflow almost stops at the distance comparable to the magnetospheric radius, r_m. This stage ends when the surface density of the flow is too high for the magnetic field to support the gas. 3) The inner flow when the magnetosphere is squashed by the gas accumulated in the front of the inflow. The accretion torus is rebuilt and a relativistic jet is reproduced. The accretion rate at this stage is lower than the hyperaccretion rate but higher than the inflow rate. We expect that during the late accretion the inner flow switches between the second and third stage and the third stage corresponds to the time when X-ray flares are produced. This cartoon illustrates the situation when the central magnetic flux is conserved (i.e., the solid lines with arrows correspond to the magnetic field lines at the center; for the clarity of the cartoon, the magnetic field lines of other flow components are not drawn.)